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Launch Vehicle and Propulsion Programs Division
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AEROSPACE SYSTEMS and MISSION ANALYSIS RESEARCH

Status Report for the Period

1 April through 30 June 1967

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Aerospace Systems and Mission Analysis Research (ASMAR) Program
Department of Aerospace and Mechanical Sciences
School of Engineering and Applied Science
PRINCETON UNIVERSITY

AEROSPACE SYSTEMS and MISSION ANALYSIS RESEARCH

Status Report for the Period 1 April through 30 June 1967

I. INTRODUCTION

A. General

During the period of this report, research of the ASMAR Program continued as previously outlined under the sponsorship of NASA/OSSA Launch Vehicle and Propulsion Programs Division (NASA Contract NASr-231). As mentioned in previous reports there has been some diversion from the Basic Program due to solar electric mission studies under separate contract (NASA Contract NSR-31-001-078). These studies will be completed as of 30 September 1967.

B. Personnel

Dr. Colin N. Gordon who has been working full time left to return to England. His two-dimensional trajectory optimization program, Gordon 1, is almost completed. Any further development will be done by Mr. George A. Hazelrigg, Jr.

Mr. John H. Campbell has undertaken the development of Lion 1, our three-dimensional trajectory optimization program. Details are contained later in this report.

Dr. Robert Vichnevetsky continues to lead the research on nuclear rocket systems analysis and is assisted by Dr. Michael D. Mintz.

Prof. Lion is continuing research on impulsive trajectories. His paper on "Sufficient Conditions for Optimal Fixed Time Impulsive Trajectories"

has been accepted for the IAF Meeting in Belgrade, Yugoslavia in September 1967.

Mr. Michael Minkoff, graduate student, has developed a program based on the previous paper of Lion and Handelsman (AIAA Paper 67-54) on the primer vector. This is an n-impulse optimization program where n is unspecified. The paper by Lion and Handelsman has been accepted for publication in the AIAA Journal. During the summer Mr. Minkoff will be with the Mission Analysis Division of OART at Ames Research Center.

Mr. Arthur E. Miller, programmer, will leave as of 31 July.

Mr. Sol M. Rocklin has completed his Master's thesis entitled "A Study of the Singularities of the Primer Vector." Mr. Rocklin received the MSE degree in June.

During the last week of April the ASMAR Group sponsored a two day conference on Trajectory Analysis and Optimization. More than fifty representatives from government, industry and other universities attended. A list of attendees is included as Appendix A. The concept of the meeting was a series of informal progress reports from selected people engaged in trajectory analysis research throughout the country. The objective was to stimulate discussion and interchange. The morning of the first day was devoted to a presentation by the members of the ASMAR Group on the work going on at Princeton. During the afternoon speakers from other groups presented half-hour discussions of work in progress. A social hour and dinner was held that evening in the New South Tower overlooking the campus. The meeting concluded the following morning with a discussion of the outstanding problems in trajectory analysis led by J. P. Layton. From all reports the meeting was well received and apparently successful in its objective.

II. SPACEFLIGHT TRAJECTORY ANALYSIS RESEARCH

A. Program Development

The primary programming effort has been devoted to writing a new trajectory optimization program, Lion 1. This is a three-dimensional, heliocentric program employing analytic coasts. Due to lack of time Prof. Lion is unable to continue primary involvement of the program; Mr. John Campbell has taken over development of the program. Since this change the rate of progress has accelerated considerably. Modifications to the program during the past three months include:

1. The numerical integration method used during thrust segments of the trajectory has been changed from a second order Milne predictor-corrector to a third order Adams-Bashforth predictor with a fourth order Adams-Moulton corrector.

2. The thrust equations have been modified to make the power vary as a function of the radius as necessary for solar electric propulsion.

3. The independent variable of the integration has been changed from time to mass ratio. With a constant integration step size in mass ratio (solar electric propulsion), the corresponding time span for each integration step varies as a function of radius. This effect makes a constant step size effective in all segments of the thrust integration.

4. Iteration logic for more accurate switching from thrust or coast segments has been included.

5. The partial derivatives have been expanded to include the partial derivatives of the final conditions with respect to VH , FMO , VJ , and the launch date.

6. Impulsive iterative capability has been added; utilizing a much improved Lambert routine.

7. The modified trajectory has been coupled to the generalized iteration and optimization routine developed at the Manned Spacecraft Center (MSC Internal Note 66-FM-131).

8. The JPL Development Ephemeris 19 has been linked to the program to provide ephemeris data for the planets Mercury through Pluto during the years 1970 through 1999.

9. The entire program has been converted for use on the IBM 360 computer.

The Program now has the capability of optimizing VJ , VH , and power level as well as the thrust program. This can be done for solar electric, nuclear electric and nuclear rocket propulsion.

While there are further additions we wish to make to this program, the main emphasis now is on exercising the program as it now stands.

Mr. Michael Minkoff, a first year graduate student, has developed an n-impulse optimization program. This program is based upon the ideas in the paper by Lion and Handelsman (AIAA Paper 67-54). This program is unique in that the number of impulses need not be specified beforehand. The program is now converging for three impulse trajectories. Mr. Minkoff is now developing the capability for more than three impulses. He is also working on a technique to speed the convergence.

B. Analytical Results

Prof. Lion has succeeded in developing an expression for the second

variation for impulsive, fixed time trajectories. This turns out to be a quadratic form in the state and control variables with linear difference equations as attached constraints. Classical linear control theory does not apply, however, since the matrix for the cost of control is singular. (Control variables for this problem are the velocity impulses and the time of these impulses.) Since most nominal trajectories will have only a small number of impulses, it is possible to use the constraints to eliminate extra degrees of freedom. Sufficient conditions for (local) optimality are that a matrix derived using this procedure be positive definite. For inverse square gravitational fields, these conditions can be checked using only algebraic equations. No integration of differential equations is required. These results will be presented before the IAF in Belgrade, Yugoslavia in September.

III. AEROSPACE SYSTEMS ANALYSIS

During this period emphasis has been placed on the analysis of the nuclear rocket propulsion system. The following items have been accomplished.

1. Development of a complete mathematical model of the thermodynamic cycle of H_2 within the nuclear rocket. This mathematical model is developed and partly programmed (M. Mintz).

2. Development of a nuclear reactor optimal mass/criticality calculation. This has resulted into a working computer program (M. Flynn). The working program is however presently working for a geometrical configuration different from that of interest in the nuclear rocket.

3. Development of performance criteria for nuclear propulsion systems based on multi-level optimization algorithm. This will permit system analysis and mission analysis to be linked via Lagrange multipliers or sensitivity functions.

4. Development of simplified mathematical model of the nuclear rocket for the development of sensitivity functions to be used in 3. (This model will eventually be replaced by the combination of 1 and 2, when completed.)

This program will be taken over by C. Kalmbach and R. Chin this fall. The necessary modifications are: (a) change from linear to cylindrical geometry and (b) change in fuel and moderator cross sections. The latter is being done by R. Chin who has spent some time this summer in computing cross sections corresponding to materials used in the nuclear rocket. These, together with the change in geometry (change in the form of the criticality matrix) will be

completed this fall by Kalmbach and Chin. The output of this program is, for each power level, the optimal core/reflector ratio to achieve minimum mass.

IV. INTERPLANETARY-PLANETARY MISSION ANALYSIS RESEARCH

Analysis of solar electric propelled missions continues to delay our studies under the Basic Program; however, some progress is being made and the solar electric work under NSR-31-001-078 will be terminated on 30 September. Some specific missions identified in the course of the solar electric studies: e.g., high power Mars and Venus orbiters, Jupiter swingbys to the outer planets, et al. and missions involving navigation, guidance and control considerations will be analyzed further under the Basic Program.

PRINCETON UNIVERSITY
Department of Aerospace and Mechanical Sciences

AEROSPACE SYSTEMS and MISSION ANALYSIS RESEARCH (ASMAR) PROGRAM

26 April 1967

Conference on Trajectory Analysis and Optimization
(Wednesday, 26 April and Thursday, 27, April 1967)

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